Constituent Quarks and systematic errors in midrapidity charged multiplicity ($dN_{ch}/d\eta$) distributions in p+p and Au+Au collisions

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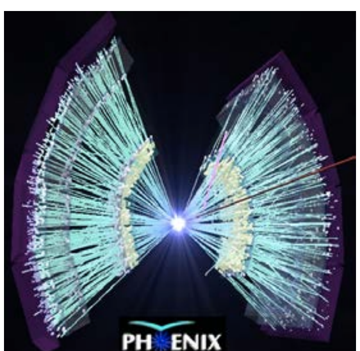


PHENIX2014 E_T distributions from PRC**89**(2014)044905
$dE_T/d\eta$ dNch/dη from PRC**93**(2016)024901

Second PHENIX paper from RHIC evolution of mid-rapidity $dE_T/d\eta$ with centrality, N_{part}

PHENIX $\sqrt{s_{NN}}$=130 GeV,
PRL87 (2001)052301

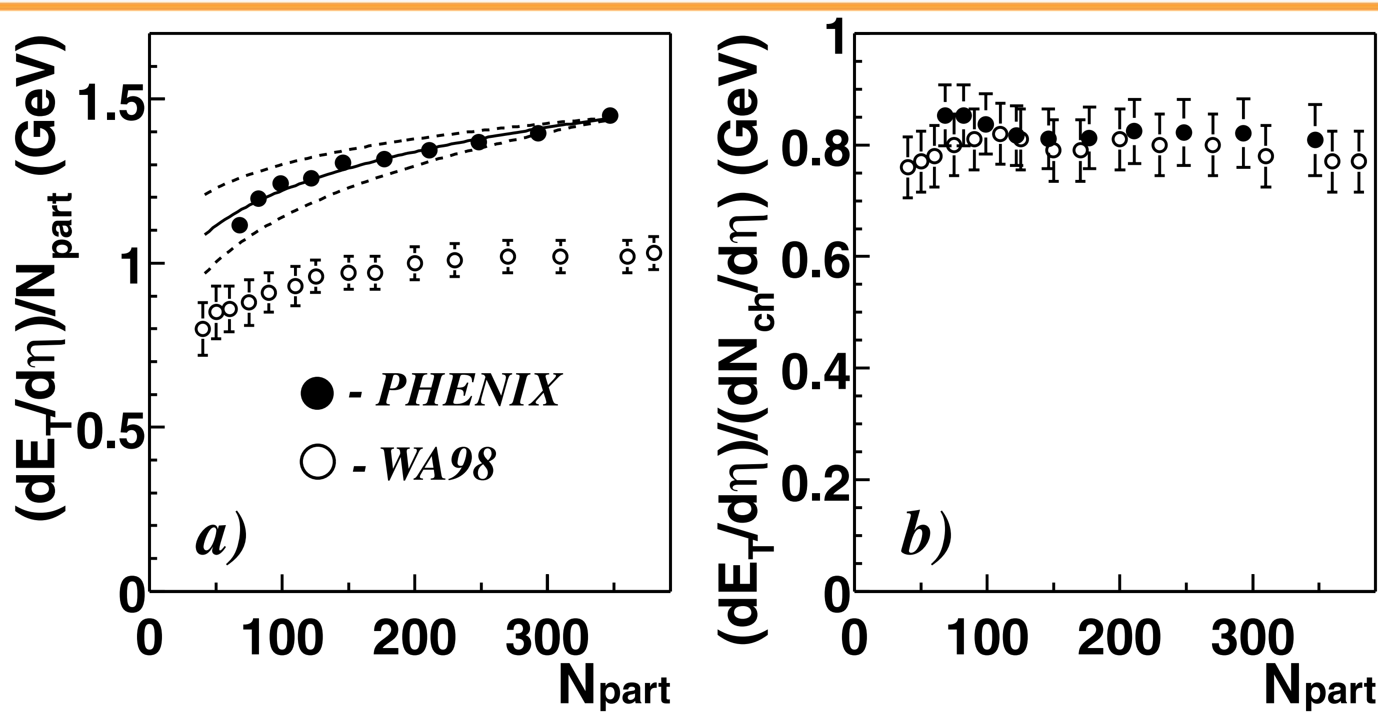
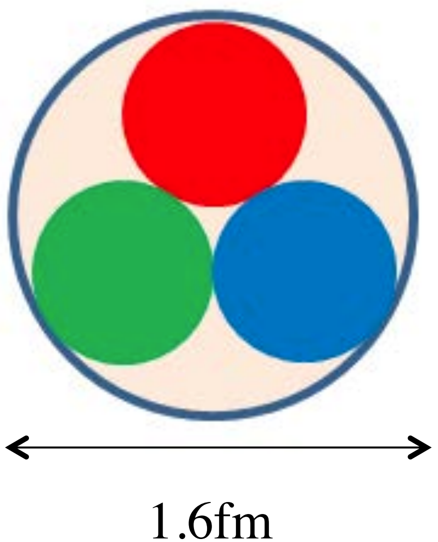


Fig. 4. (a) PHENIX transverse energy density per participant $dE_T/d\eta/N_{part}$ for Au+Au at $\sqrt{s_{NN}}$=130 GeV as a function of N_{part}, the number of participants, compared to the data of WA98 for Pb+Pb collisions at $\sqrt{s_{NN}}$=17.2 GeV. The solid line is the N_{part}^{α} best fit and the dashed lines represent the effect of the $\pm 1\sigma$ N_{part}-dependent systematic errors for $dE_T/d\eta$ and N_{part}. **These are the Type B correlated systematic errors, all points move together by the same fraction of the systematic error at each point.**

What are Constituent Quarks?

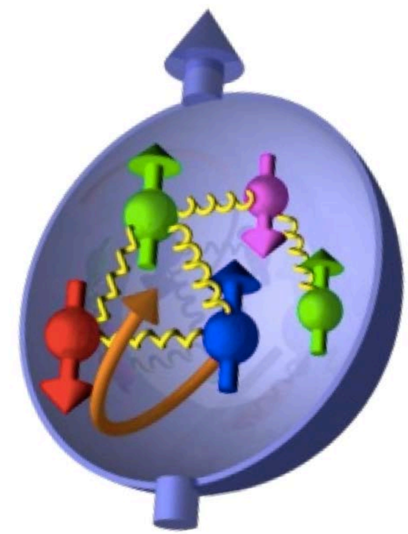
Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud. These are relevant for static properties and soft physics, low $Q^2<2$ GeV^2 ; resolution> 0.14fm

For hard-scattering, $p_T>2$ GeV/c, $Q^2=2p_T{}^2>8$ GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible



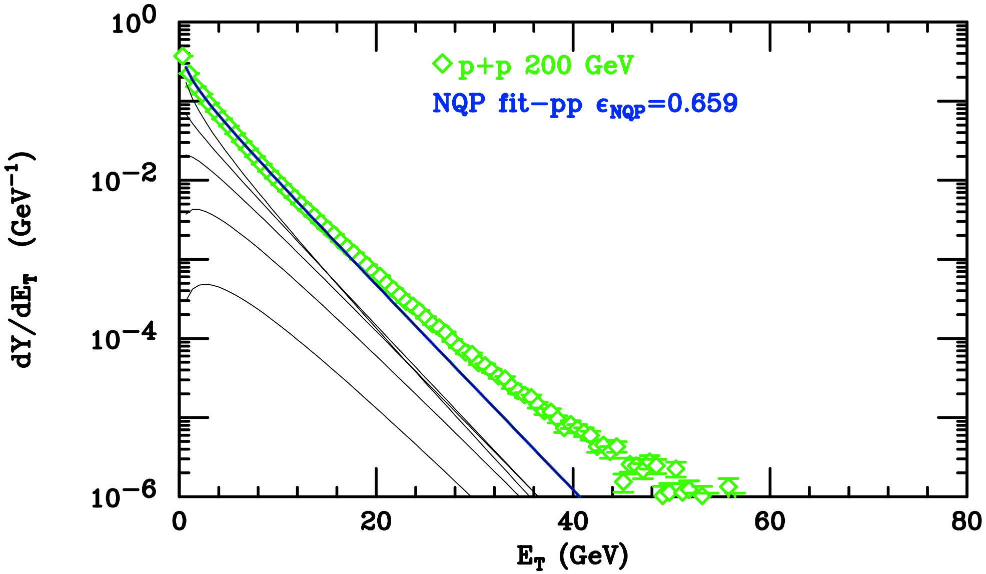
Resolution ~0.5fm

Resolution ~0.1fm



Resolution <0.07fm

PHENIX NQP model: Data driven pp→ dAu, AuAu

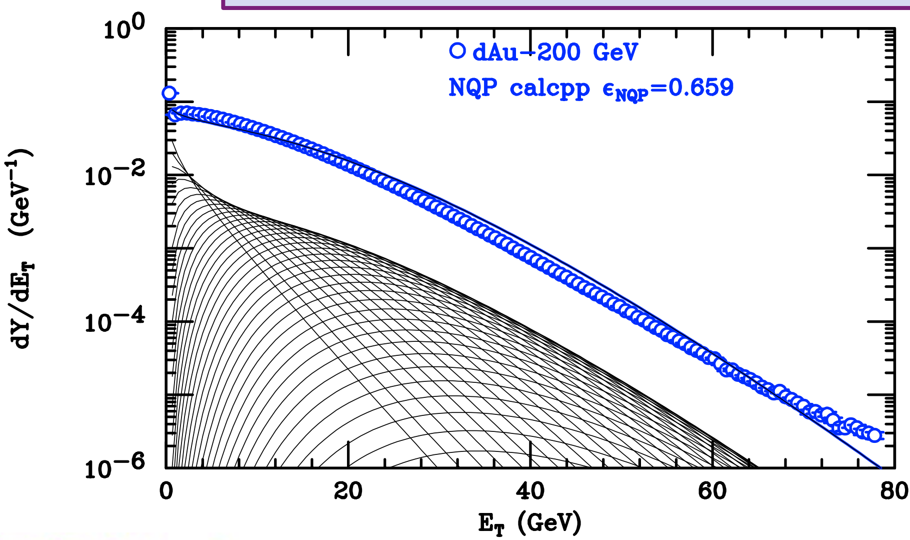


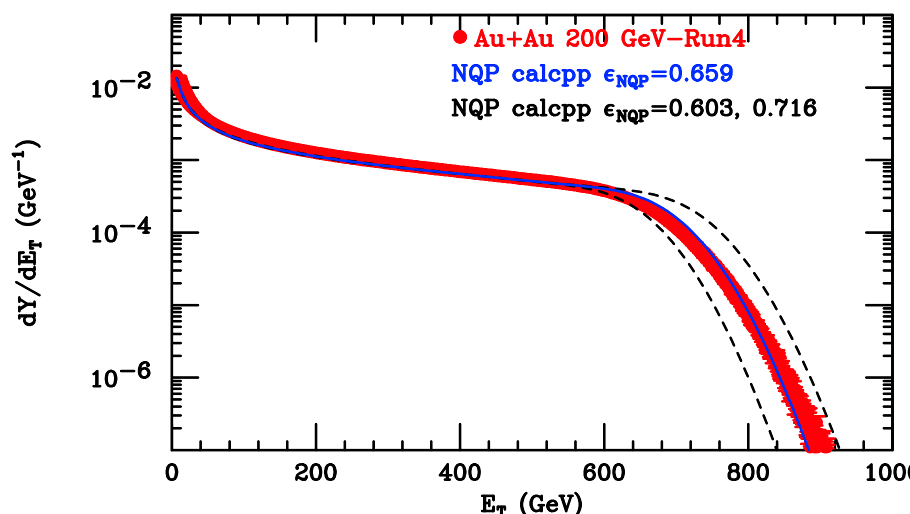
PHENIX2014 E_T distributions from PRC**89** (2014) 044905

1) Generate 3 constituent quarks around nucleon position, distributed according to proton charge distribution for pp, dA, AA

2) Deconvolute p-p E_T distribution to the sum of 2—6 quark participant (QP) E_T distributions taken as Γ distributions

3) Calculate dAu and AuAu E_T distributions as sum of QP E_T distributions





How we generated the quarks around the nucleon position in PHENIX2014

PHENIX2014 [6], the spatial positions of the the three quarks were generated around the position of each nucleon in the Glauber monte carlo calculations for $p+p$, d+Au and Au+Au collisions using the proton charge distribution corresponding to the Fourier transform of the form factor of the proton [24]:

$$d^3\mathcal{P}/d^3r = \rho^{\rm proton}(r) = \rho_0^{\rm proton} \times \exp(-ar), \tag{4}$$

where $a = \sqrt{12}/r_m = 4.27 \text{ fm}^{-1}$ and $r_m = 0.81$ fm is the r.m.s radius of the proton weighted according to charge [2]

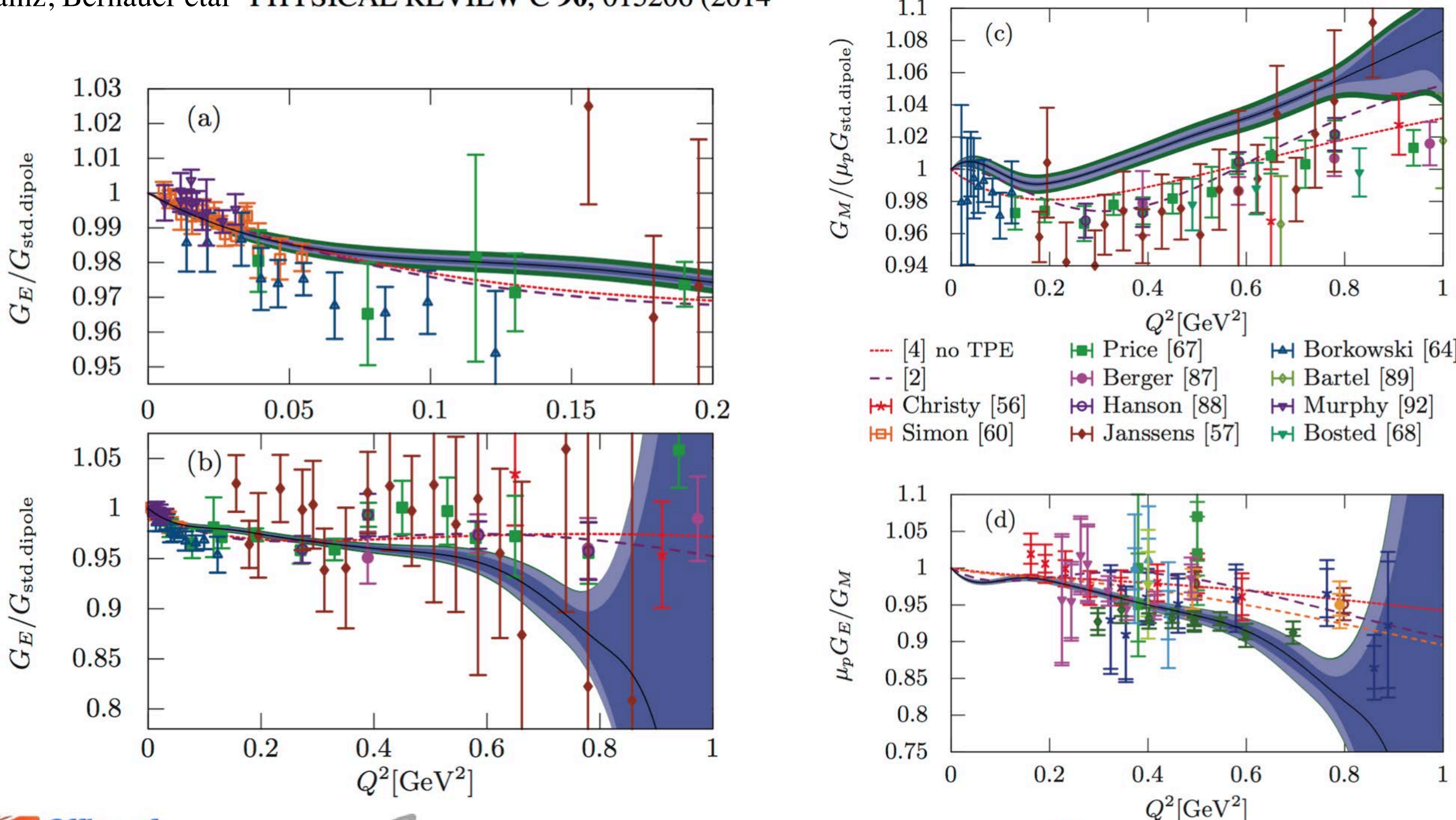
$$r_m = \int_0^\infty r^2 \times 4\pi r^2 \rho^{\rm proton}(r) dr \quad . \tag{5}$$

The corresponding proton form factor is the Hofstadter dipole fit [25] now known as the standard dipole [26]:

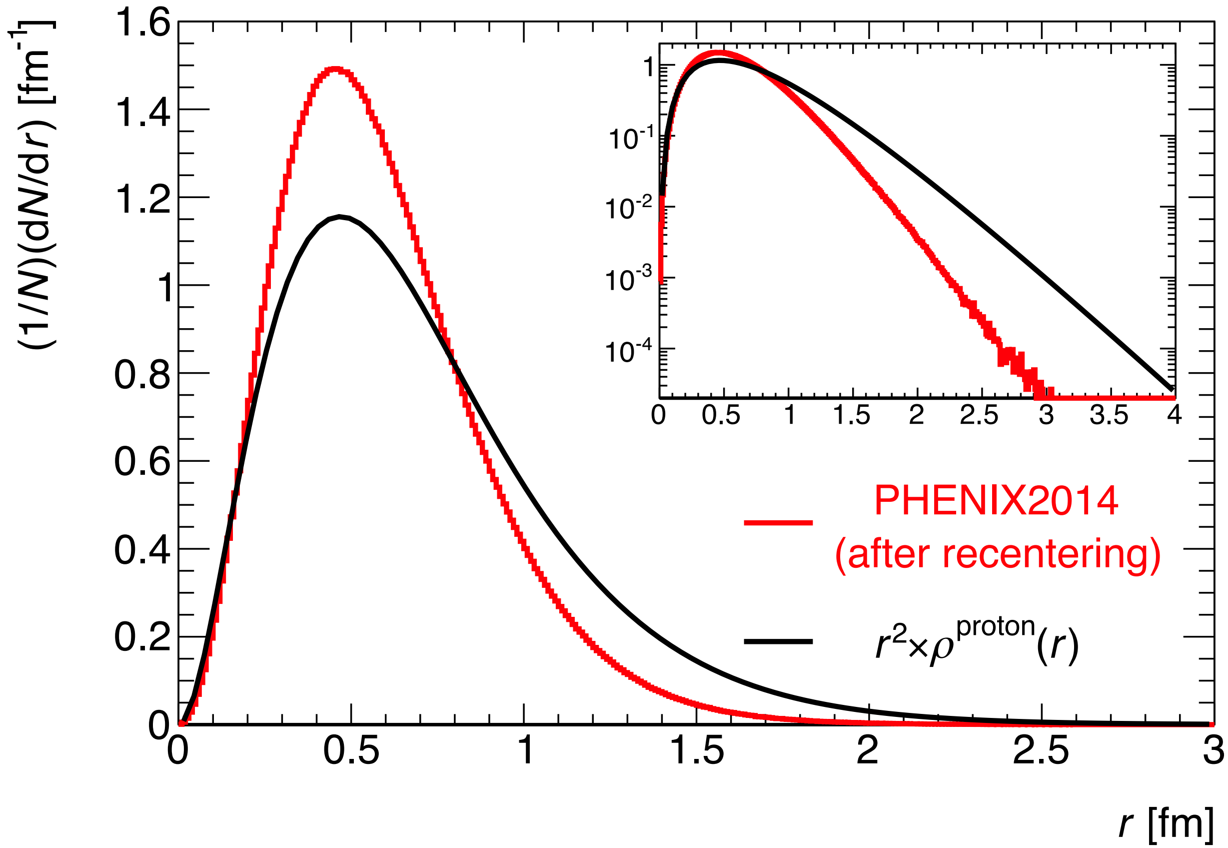
$$G_E(Q^2) = G_M(Q^2)/\mu = \frac{1}{(1+\frac{Q^2}{0.71\mathrm{GeV}^2})^2} \qquad (6)$$

Note that dipole fit agrees with G_E,G_M data to within a few % for $Q^2 \leq 1$ GeV^2. The `famous' radius anomaly is the upslope for $Q^2 \leq 0.1$ in (b)

Mainz, Bernauer etal PHYSICAL REVIEW C **90**, 015206 (2014



Radial distribution of the quarks about the c.m. for PHENIX2014 compared to $r^2\rho^{proton}(r) = r^2 \exp -4.27r$



- The radial distribution about the c.m. of the 3 generated quarks is not correct.

New centered Methods-PHENIX2014 data

PHYSICAL REVIEW C **93**, 054910 (2016)

Tests of constituent-quark generation methods which maintain both the nucleon center of mass and the desired radial distribution in Monte Carlo Glauber models

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(Received 29 March 2016; published 23 May 2016)

Several methods of generating three constituent quarks in a nucleon are evaluated which explicitly maintain the nucleon's center of mass and desired radial distribution and can be used within Monte Carlo Glauber frameworks. The geometric models provided by each method are used to generate distributions over the number of constituent quark participants ($N_{\rm qp}$) in $p + p$, d + Au, and Au + Au collisions. The results are compared with each other and to a previous result of $N_{\rm qp}$ calculations, without this explicit constraint, used in measurements of $\sqrt{s_{NN}} = 200$ GeV $p + p$, d + Au, and Au + Au collisions at the BNL Relativistic Heavy Ion Collider.

DOI: 10.1103/PhysRevC.93.054910

DVP—Empirical Radial distribution Recentered

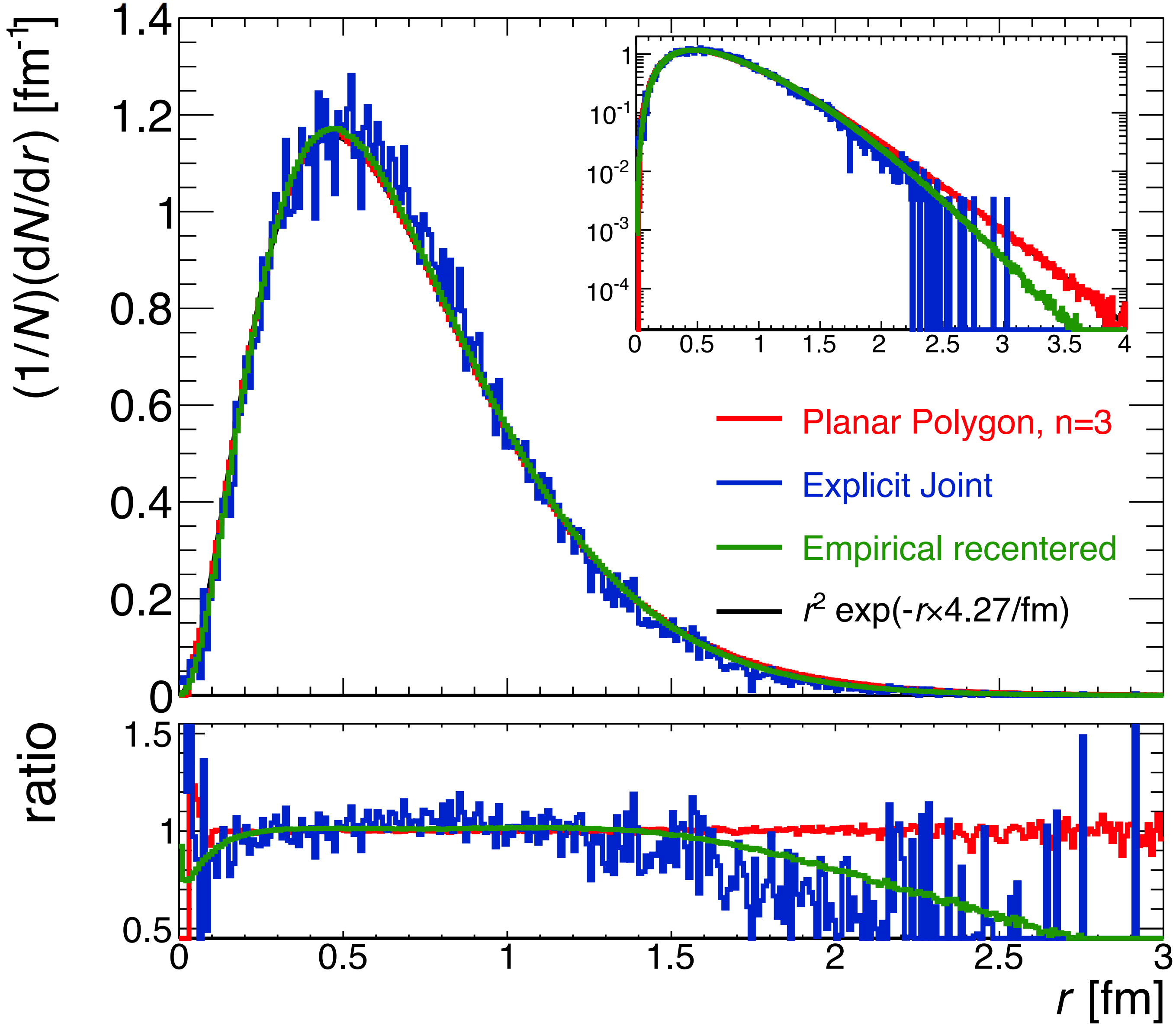
$$f(r) = r^2\rho(r) = r^2 e^{-4.27r}(1.21466 - 1.888r + 2.03r^2)$$
$$(1 + 1.0/r - 0.03/r^2)(1 + 0.15r)$$

where r is the radial position of the quark in fm.

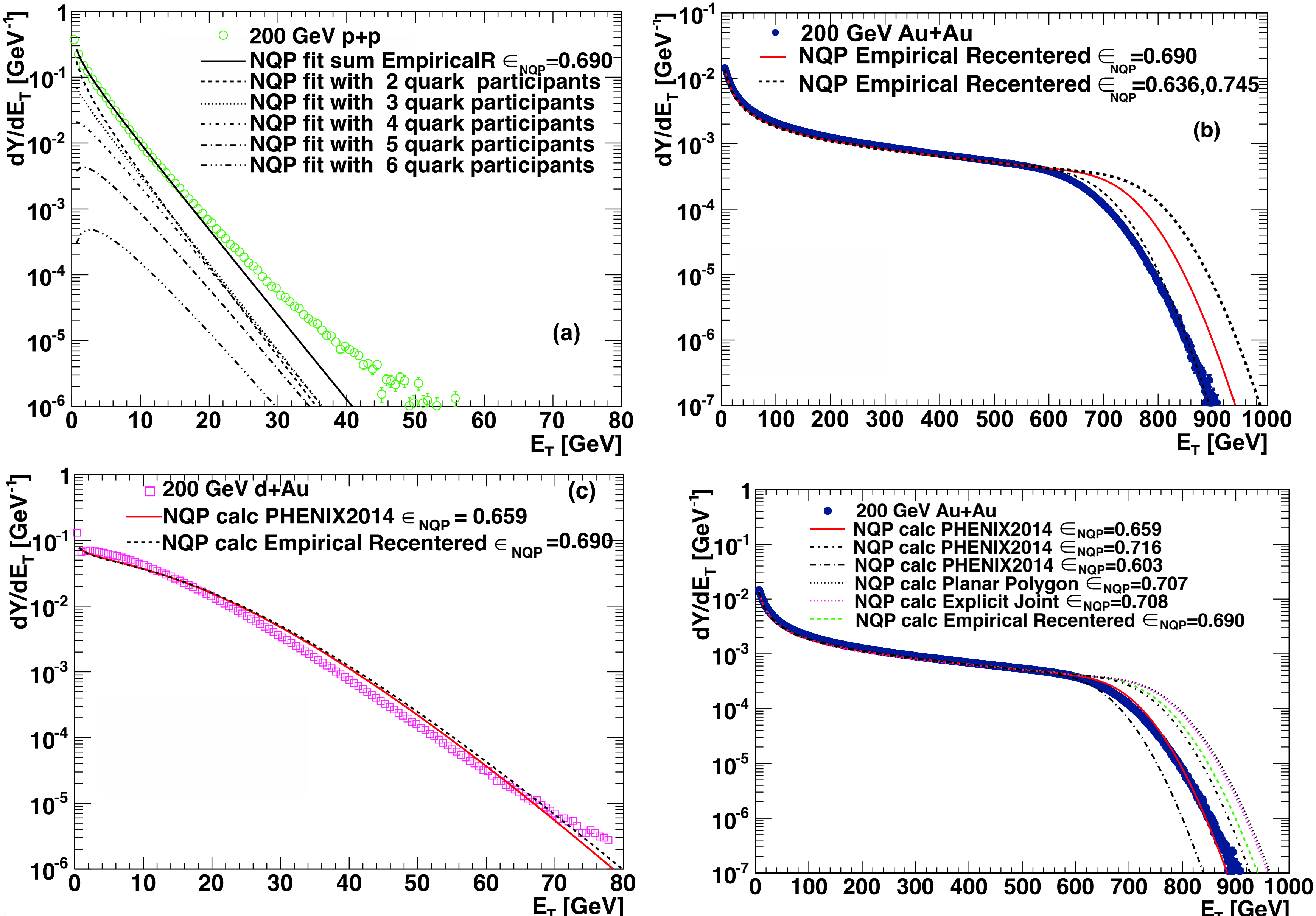
- the three constituent-quark positions are drawn independently from the auxiliary function *f(r)* above. Then the center of mass of the generated three-quark system is re-centered to the original nucleon position.

This function was derived through an iterative, empirical approach. For a given test function f^{test}(r), the resulting radial distribution ϱ^{test}(r) was compared to the desired distribution ϱ^{proton}(r) in Eq. 4. The ratio ϱ^{test}(r) / ϱ^{proton}(r) was parameterized with a polynomial function of *r* or *1/r*, and the test function was updated by multiplying it with this parametrized functional form. Then, the procedure was repeated with the updated test function used to generate an updated ϱ^{\rm test}(r) until the ratio ϱ^{test}(r) / ϱ^{proton}(r) was sufficiently close to unity over a wide range of r values.

New Radial quark distributions about the c.m.

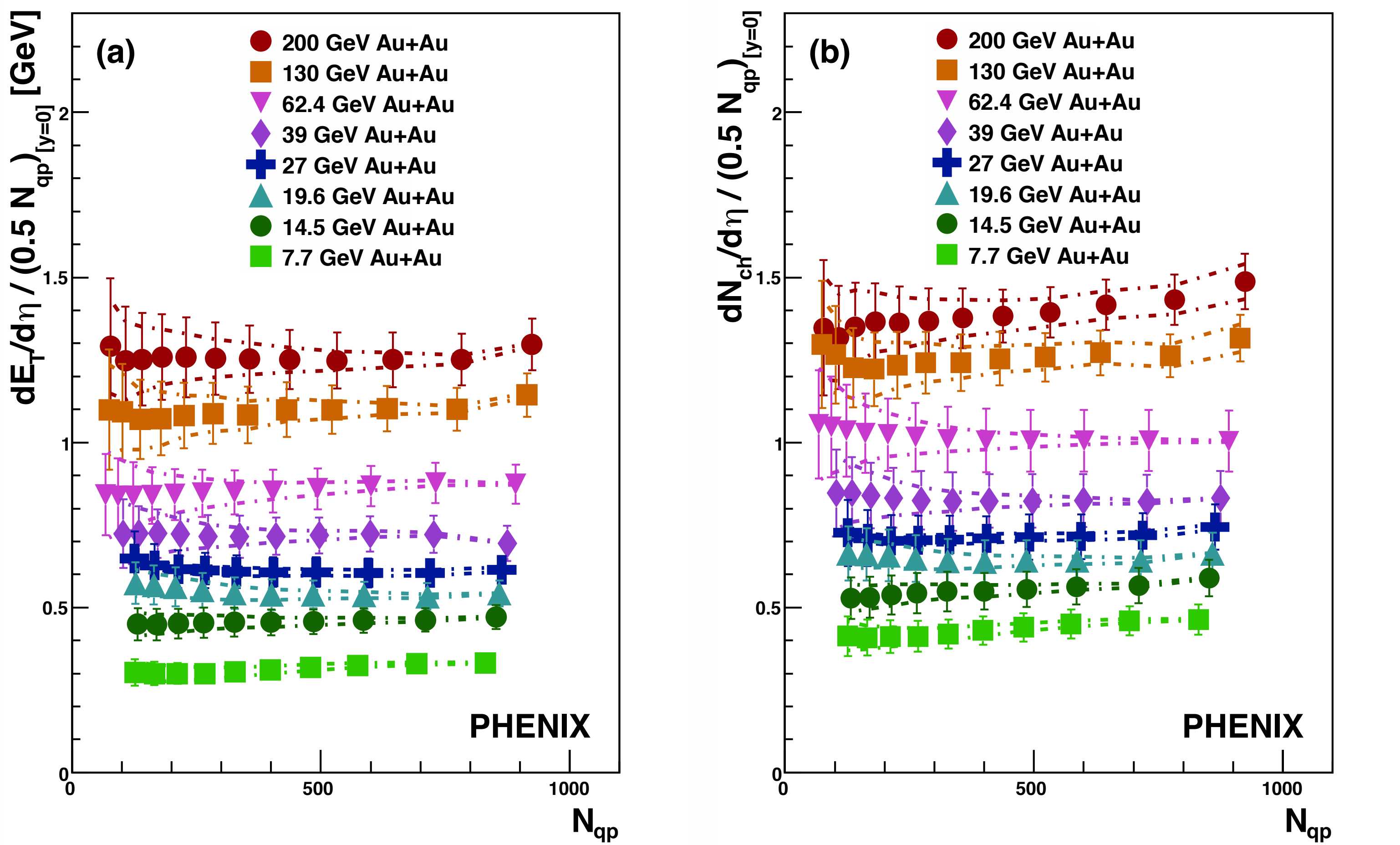


NQP centered with PHENIX2014 data



all work within ~1 standard deviation

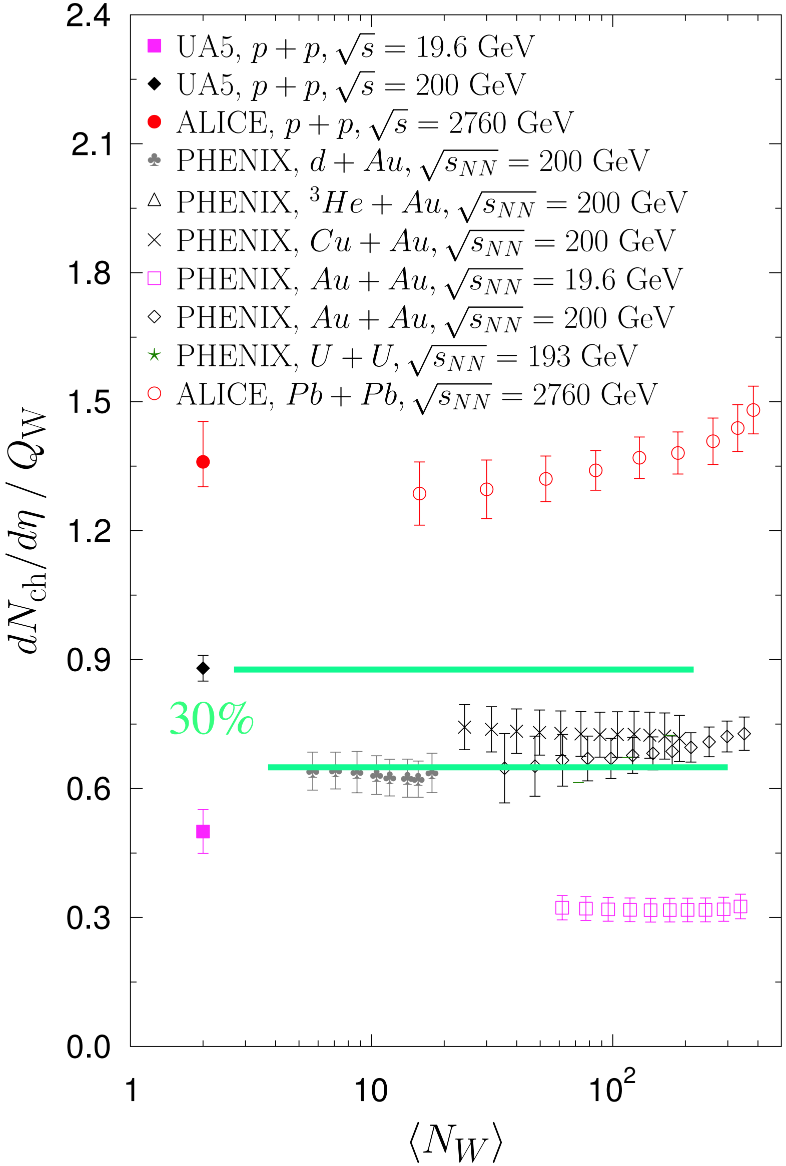
Constituent-quark-participant scaling vs. N_{qp}



PHENIX PRC93(2016)024901

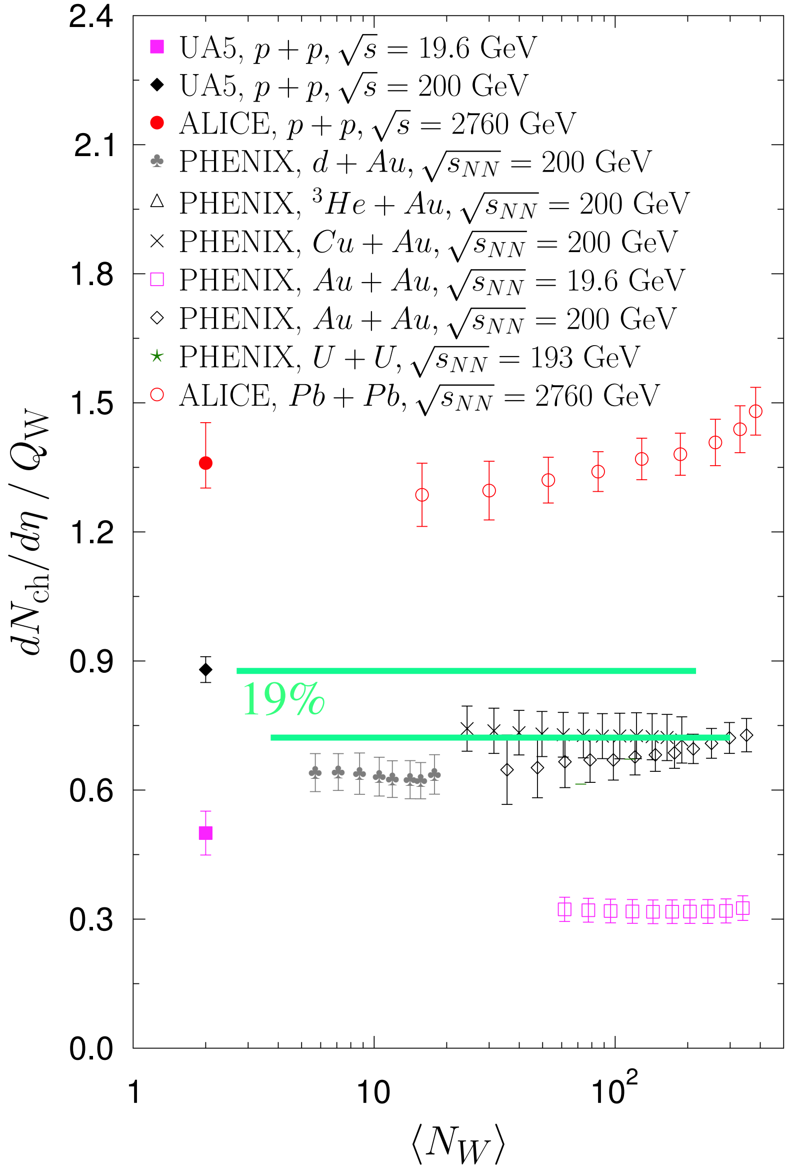
Uses Empirical Recentered---now standard

Disagreement from another NQP calculation?



Bozek, Broniowski, Rybczynski PRC94(2016)014902 do a constituent quark participant calculation which they call Q_W (wounded quark) and find that it works for ALICE Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV "but we note in Fig. 1 that at $\sqrt{s_{NN}}$=200 GeV the corresponding p + p point is higher by about 30% from the band of other reactions"(only from the lowest AuAu point)

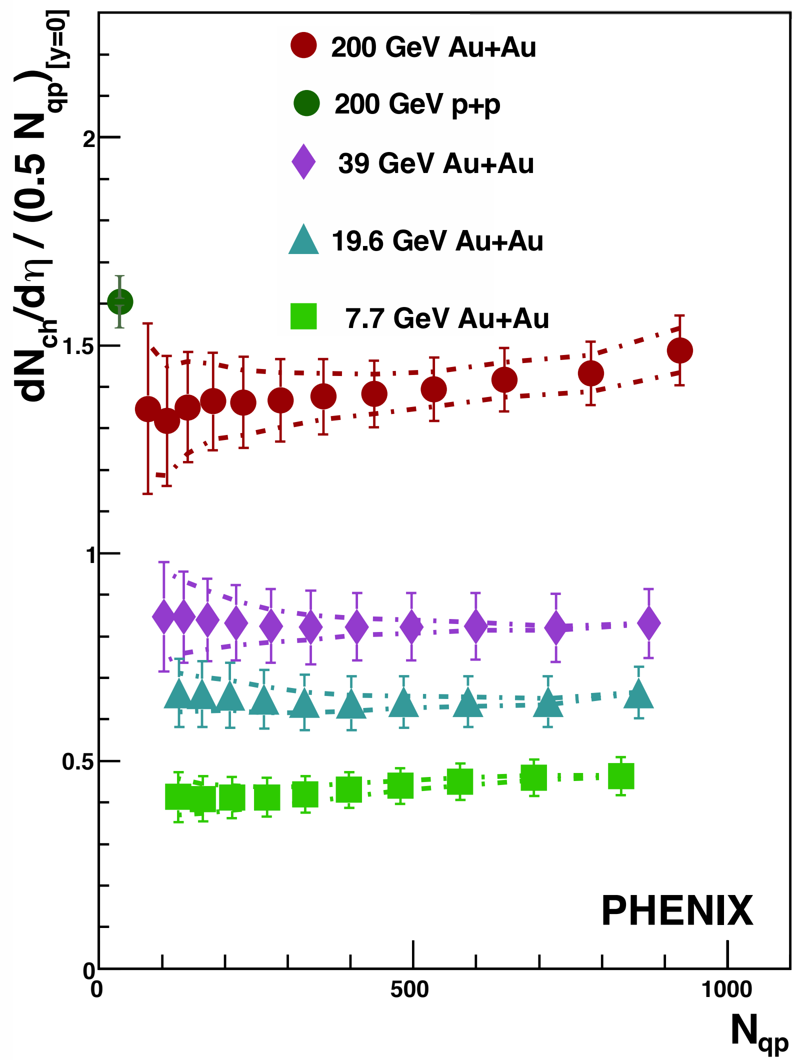
Disagreement from another NQP calculation?



<u>Only from the lowest AuAu point</u>

Of course I noted that they only used our tabulated statistical errors but left out our Type B correlated systematics shown on our plots where **all** the data points can be moved up to the top of their syserror bars with the cost of 1 σ, so that the ratio of the p+p to lowest AuAu point is 1.19±0.17 statistical, or 1.33±0.22 if we simply add the sys and stat in quadrature. i.e. 33±22%≈30% But this difference is not significant.

Disagreement from another NQP calculation? Here is our calculation.



We actually didn't calculate the p+p value in PRC93 (2016) 024901, but did show the systematic errors on the plot. So here they are along with the p+p calculation from PRC93 (2016) 054910 using the same UA5 pbar+p $dN_{ch}/d\eta$ =2.23±0.08 at $\sqrt{s}$=200 GeV with a p+p/Au+Au ratio of 1.19±0.19±0.16 sys i.e. agreement to ≈ 1 σ for all the data points at 200 GeV Au+Au.

As far as I can tell BB&R use r_m=0.94 fm for the proton rms radius in Eq 4 and a gaussian wounding profile for a q+q collision--Not the standard Glauber.

Conclusions

- The Constituent Quark Participant Model (N_{qp}) works at mid-rapidity for A+B collisions in the range (~20 GeV) 39 GeV< $\sqrt{s_{NN}}$< 5.02 TeV.
- Experiments generally all use the same Glauber M.C. but the BB&R's M.C. is different for q+q scattering leading to somewhat different results.
- Attention must be paid to systematic errors.
- How can the event-by-event proton radius variations and quark-quark correlations used in Constituent Quark Glauber models be measured?

Details on “Disagreement” of NQP calculations

Table 1: $N_{\rm qp}$ in p+p

paper p+p	$\sqrt{s_{NN}}$ (GeV)	$\sigma_{nn}^{\rm inel}$ (mb)	r_m (fm)	$\sigma_{qq}^{\rm inel}$ (mb) (GeV)	$\langle N_{\rm qp}\rangle$
PX2014 Phys. Rev. C**89**, 044905 (2014)	200	42.0	0.81	9.36	2.99
MPTS Phys. Rev. C**93**, 054910 (2016)	200	42.3	0.81	8.17	2.78
Loizides Phys. Rev. C**94**, 024914 (2016)	200	42.	0.81	8.1	2.8
BB&R Phys. Rev. C**94**, 014902 (2016)	200	41.3	0.94	7.0	2.60

reaction	dn/deta	err	sys	QW	err	
p+p Bozek	2.29	0.08		2.6		
p+pMJTBozek	2.23	0.08		2.6		
p+p MPTS	2.23	0.08		2.78		
cent 55-60				QW	err	
AuAu Bozek	52.2	6.5	4.88	80.65		
AuAuPX	52.2	6.5	4.88	77.5	6.8	
	dnch/QW	err				
p+p Bozek	0.881	0.031				
p+pMJTBozek	0.858	0.031				
p+p MPTS	0.802	0.029				
	dnch/QW	stat	sys			
AuAu Bozek	0.647	0.081	0.061			
AuAuPX	0.674	0.103	0.086			
		stat	sys	stat+sys	shift sys	stat
pp/Au Bozek	**1.361**	0.176	0.136	**0.222**	**1.225**	**0.176**
ppmjtB/AuB	**1.325**	0.172	0.133	**0.217**	**1.192**	**0.172**
pp/AuAu PX	**1.191**	0.186	0.159	**0.245**	**1.032**	**0.186**

EXTRAS

Physics of A+A collisions c. 1980

- The nucleus is transparent, incident protons pass through, make many successive collisions and come out the other side

- Uncertainty principle and time dilation prevent cascading of produced particles in relativistic collisions $\gamma\ h/m_\pi c > 10$fm even at AGS energies: particle production takes place outside the Nucleus in a p+A reaction.

With 2 additional assumptions:

- An excited nucleon interacts with the same cross section as an unexcited nucleon.

- Successive collisions of the excited nucleon do not affect the excited state or its eventual fragmentation products

The conclusion is that the fundamental element for particle production in nuclear collisions is the excited nucleon and that the multiplicity is proportional to the number of excited nucleons **=Wounded Nucleon Model (Npart)**

Extreme Independent Models

- **Extreme-Independent models:** separate nuclear geometry and fundamental elements of particle production.
- Nuclear Geometry represented by relative probability w_n per B+A interaction for a given number n of fundamental elements.
- I will discuss models with 3 different fundamental elements:
  - ✓**Wounded Nucleon Model (WNM)** - number of participants N_{part}
  - ✓**Quark Part. Model (NQP),** -number of constituent-quark participants N_{qp}
  - ✓**Additive Quark Model (AQM),** color-strings between quark participants in projectile & target: constraint: one string per qp → **projectile quark participants**.
- AQM & NQP cannot be distinguished for symmetric collisions, since projectile and target have the same number of struck quarks. Need asymmetric collisions, *e.g*, d+Au,

Implementation

- The dynamics of the fundamental elementary process are taken from the data: e.g. the measured E_T distribution for a p-p collision represents: 2 participants (WNM); **a predictable convolution of constituent-quark-participants (Nqp)**; or projectile quark participants (AQM).

- The above bullet is why I like these models: a Glauber calculation and a p-p measurement provide a prediction for A+A **in the same detector!**

I verified the dipole fit in my PhD thesis

μ+p elastic scattering

I even used a detector simulation

errors. Tracks generated by the program were traced through the detection apparatus, and the simulated events were then put through the same reconstruction program as were the real events. The characteristics of Monte-Carlo-generated events and real events were then compared in detail in order to establish the validity of the method. For example, it was verified that the simulated and real events gave the same distributions in the coplanarity and copunctuality variables. Most definitive, however, was

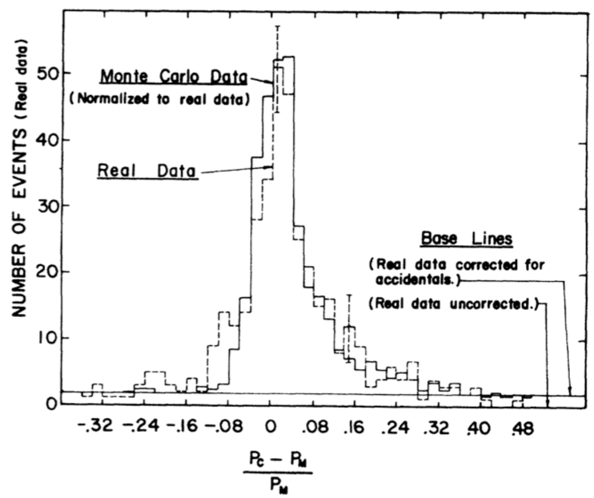


FIG. 2. Frequency distributions of real and simulated (Monte-Carlo) scattering events, versus $(P_c - P_m)/P_m$. The shift of baseline for the real events is the result of subtracting the accidental coincidences (see text), which have a flat distribution. The Monte-Carlo distribution has been normalized to have the same area as the real distribution after correction.

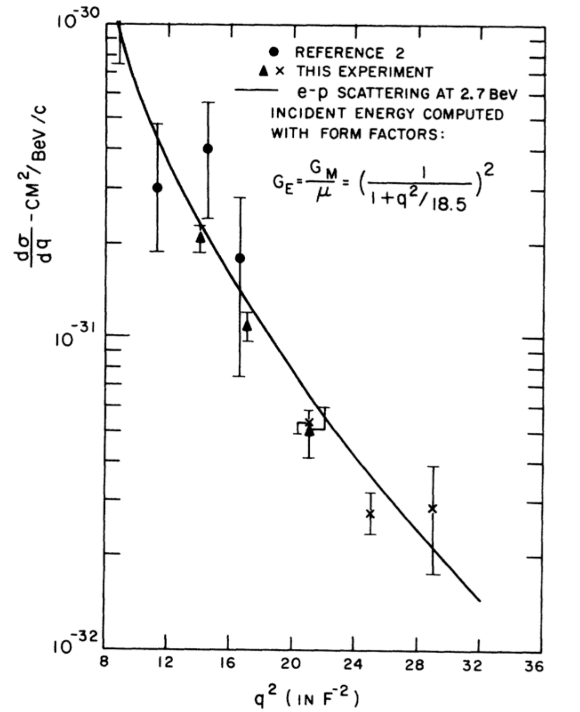


FIG. 3. Comparison of muon cross section $(d\sigma/dq)$ with the Rosenbluth prediction computed with a phenomenological fit to proton form factors. The two results at $q^2 = 20$ F^{-2} represent the overlap of two separate runs, medium-q^2 and high-q^2, differing in the thickness of absorber in front of the range chamber (Fig. 1). The expressions for G_E and G_M were chosen to fit low-q^2 e-p scattering data [L. N. Hand, D. G. Miller, and Richard Wilson, Rev. Mod. Phys. 35, 335 (1963)], and were found to fit data[7] with $q^2 \geq 20$ F^{-2} as well as the more commonly used form made up of resonance terms. Results of earlier experiments are also shown.

726

Cool, Maschke, Lederman, Tannenbaum, Ellsworth, Melissinos, Tinlot, Yamanouchi PRL14(1965)724

Previous analyses have shown that Quark Participant Model works in Au+Au but could have been the AQM

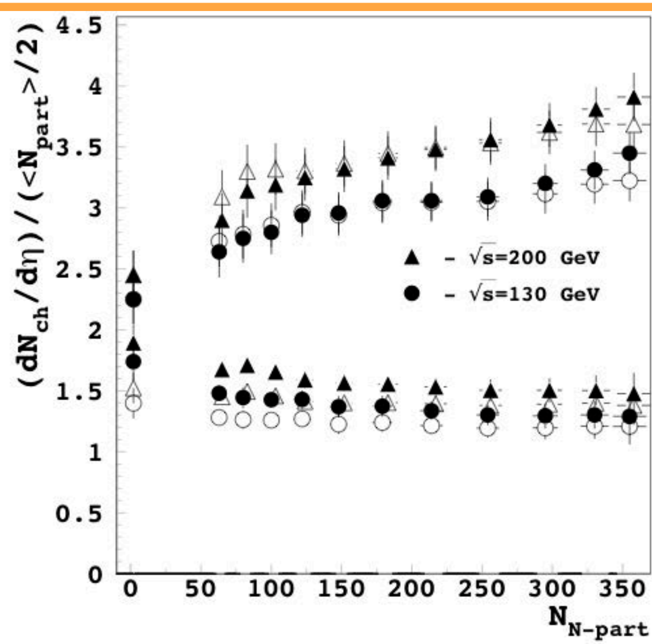
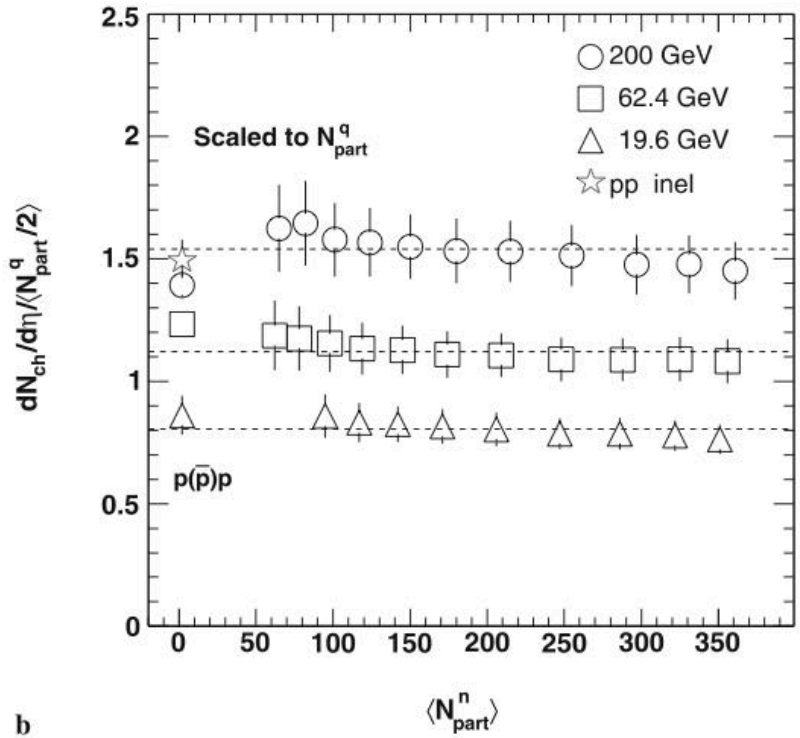


FIG. 3. (Color online) N_{ch} per nucleon and quark participant pair vs centrality. The results for quark participant pair are shown for σ_{qq}=4.56 mb (solid symbols) and σ_{qq}=6 mb (open symbols).



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Eremin&Voloshin, PRC **67** (2003) 064905

Nouicer, EPJC **49** (2007) 281

These analyses didn't do entire distributions but only centrality-cut averages. Also they just generated 3 times the number of nucleons in a nucleus according to the Au nuclear density and called them constituent quarks then let them interact with the conventional q+q cross section $\sigma_{q+q}=\sigma_{N+N}/9$. The p+p result used constant radial density in a proton taken as a hard sphere with r<0.8fm.

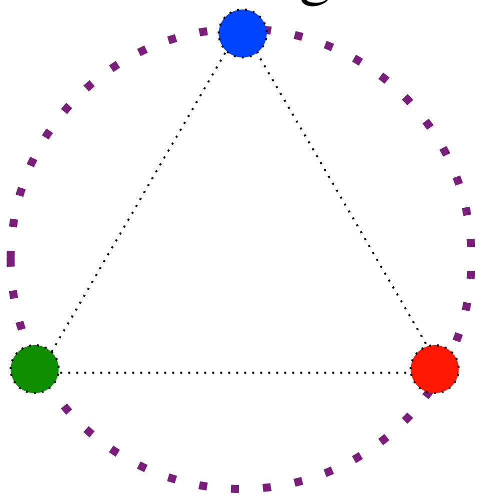
We got a comment from Adam Bzdak via Pete Steinberg 6 months after the paper appeared in PRC that our method didn't preserve the radial charge distribution about the c.m. of the three generated quarks

- This statement is correct so several of us got together to figure out how to generate 3 quarks about a nucleon that would preserve the c.m. position and the charge distribution about this c.m and how this would affect our results from PHENIX2014.

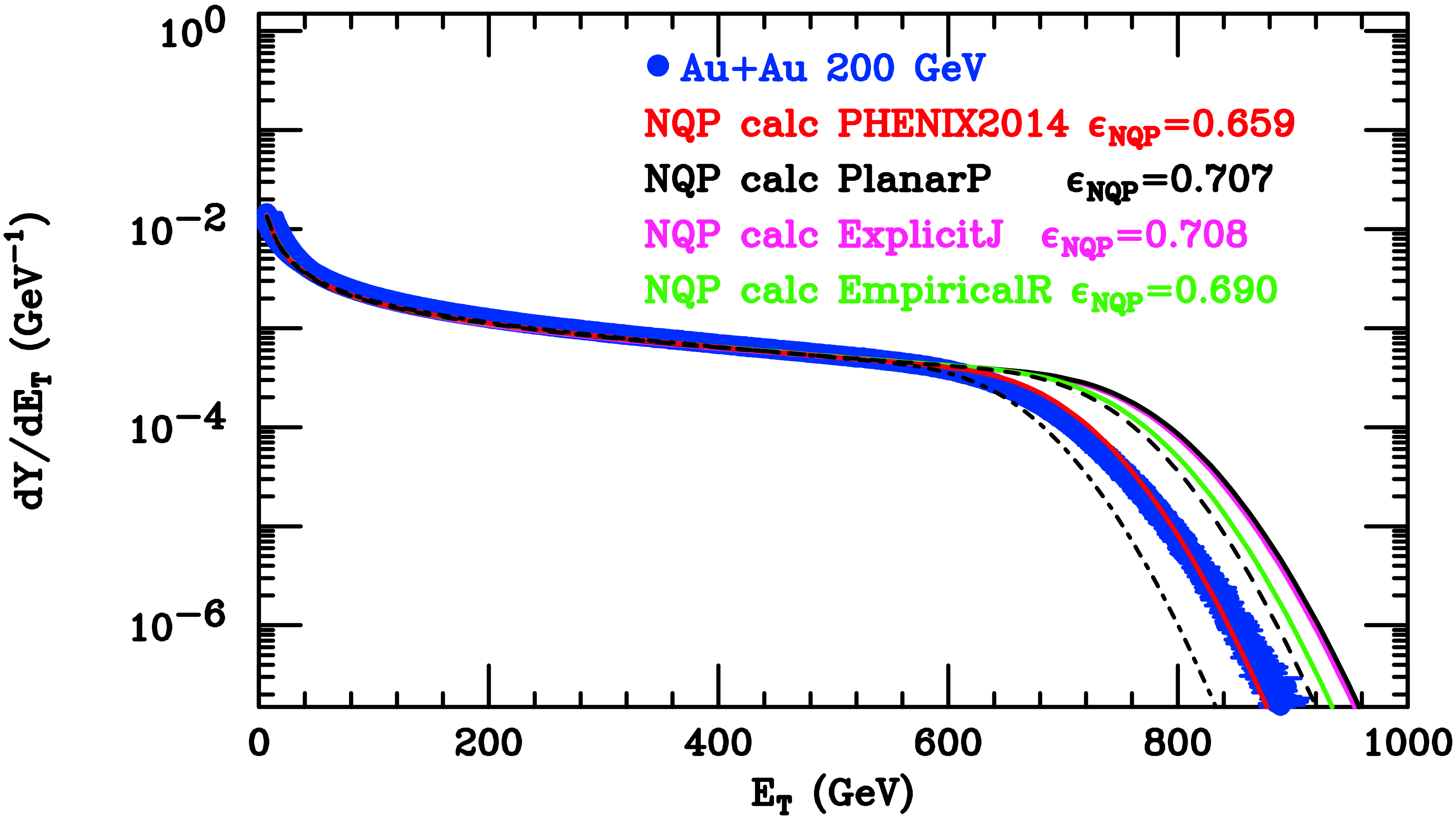
- We found 3 new methods that preserve both the original proton c.m. with the correct charge distributions about the c.m. "Planar Polygon", "Explicit Joint", "Empirical Recentered" I discuss 2. See Mitchell, Perepelitsa, Tannenbaum and Stankus PRC93,054910 (2016)

Planar Polygon

Generate one quark at (r,0,0) with r drawn from r^2 e^{-4.27r}. Then instead of generating cos θ and Φ at random and repeating for the two other quarks as was done by PHENIX2014, imagine that this quark lies on a ring of radius r from the origin and place the two other quarks on the ring at angles spaced by $2\pi/3$ radians. Then randomize the orientation of the 3-quark ring spherically symmetric about the origin. This guarantees that the radial density distribution is correct about the origin and the center of mass of the three quarks is at the origin but leaves three quark triplet on each trial forming an equilateral triangle on the plane of the ring.

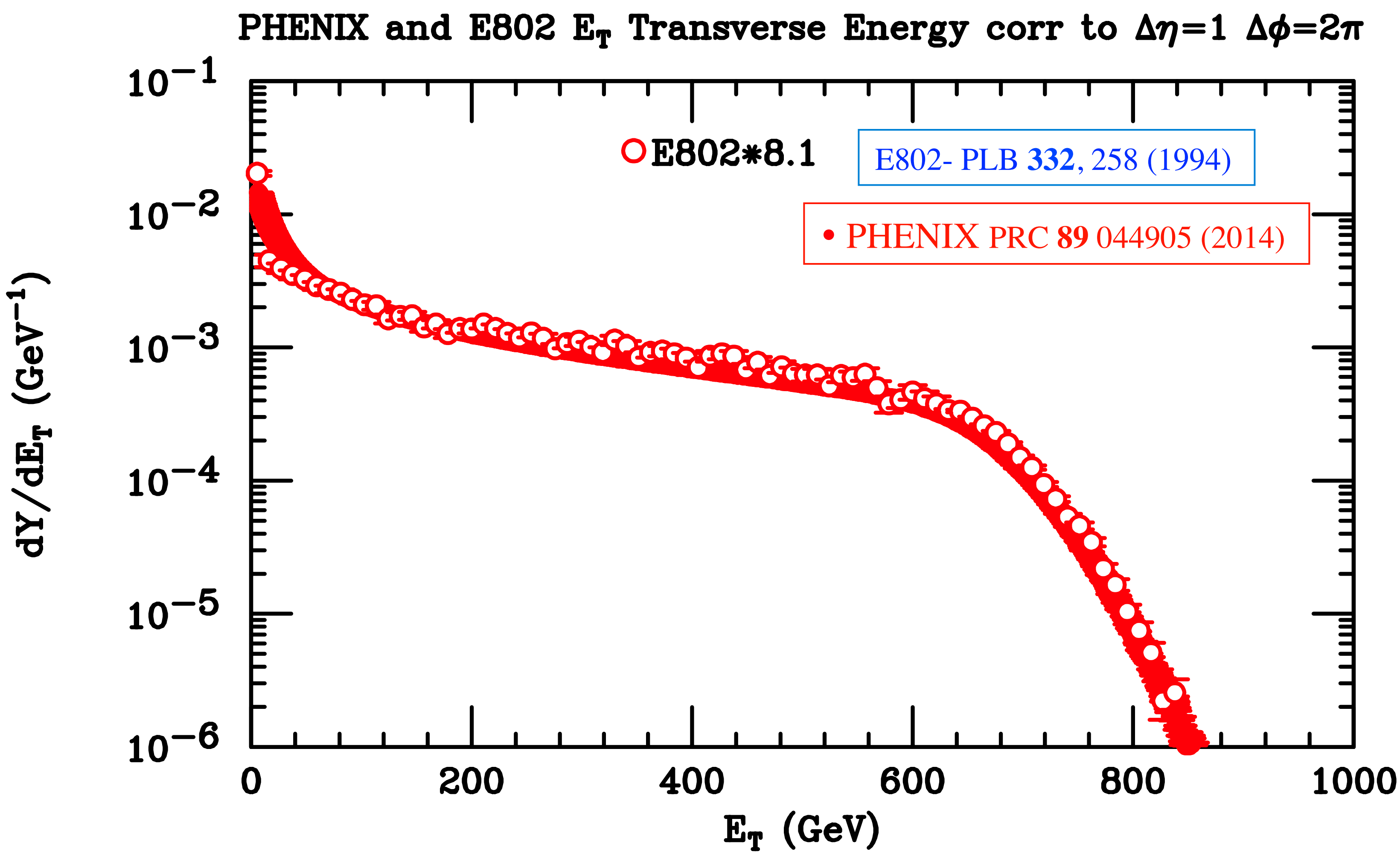


Au+Au calculation all methods



surprisingly the most complicated Explicit J and simplest Planar P are virtually identical. EmpiricalR is ~within 1 σ of PX2014

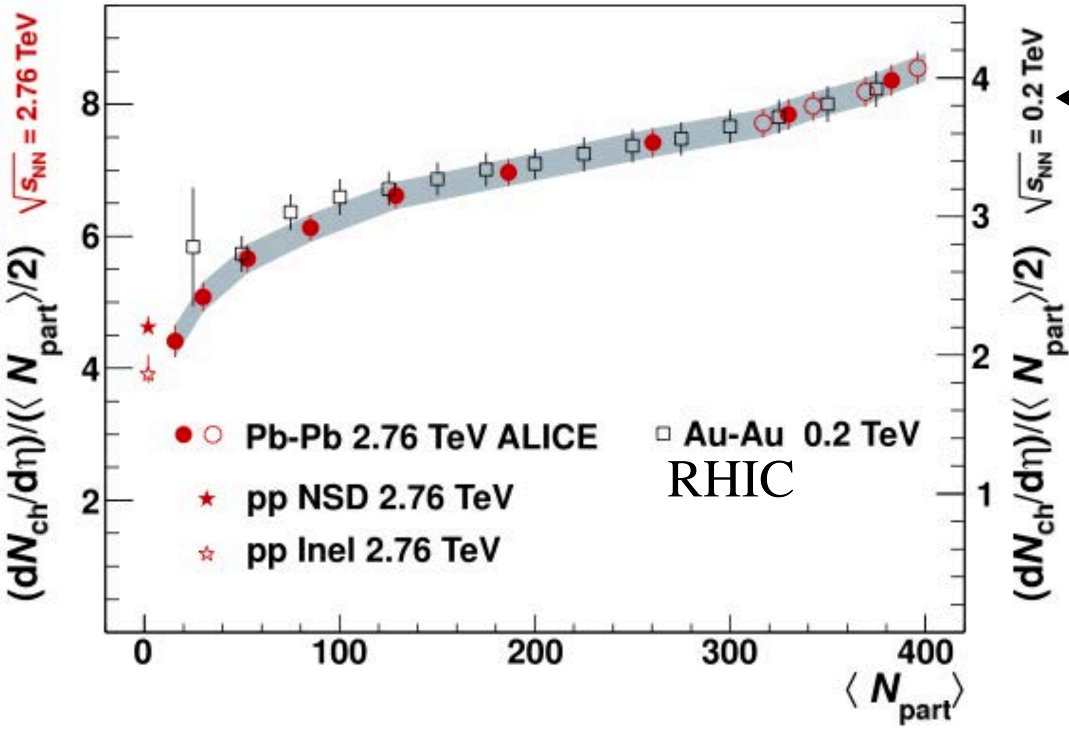
Au+Au E_T spectra at AGS $\sqrt{s_{NN}}$=5.4 GeV and RHIC 200 GeV are the same shape!!!



But following the style of the CERN fixed target results at c. 2000, we stopped plotting distributions [PRL87,052301(2001)] and gave results as $(dE_T/d\eta)/(0.5Npart)$ vs. Npart

Important Observation 2.76TeV cf. 200 GeV

ALICE $\sqrt{s_{NN}}$=2.76 TeV
PRL 106(2011)032301



- **Exactly the same shape vs. *N_{part}*** although $<N_{coll}>$ is a factor of 1.6 larger and the hard-scattering cross section is considerably larger.
  - ✓ PHENIX (2001) $dN_{ch}/d\eta \sim N_{part}^{\alpha}$ with α=1.16±0.04 at $\sqrt{s_{NN}}$=130 GeV
  - ✓ ALICE (2013) $dN_{ch}/d\eta \sim N_{part}^{\alpha}$ with α=1.19±0.02 at $\sqrt{s_{NN}}$=2760 GeV

- Strongly argues against a hard-scattering component and for a Nuclear Geometrical Effect.

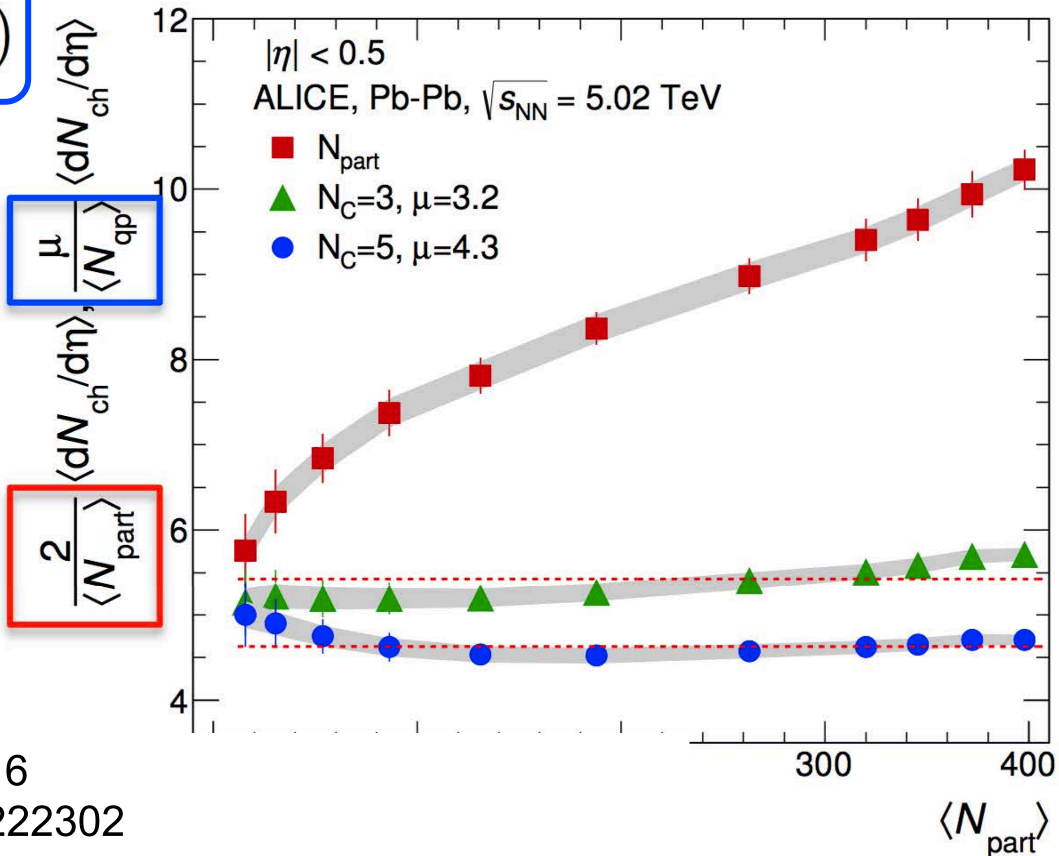
Agreement from ALICE

Glauber MC with quark scaling [10]

Single quark position determined with proton density:

$$\boxed{\rho(r) = \rho_0^{proton} \exp(-a \cdot r)}$$

particle multiplicity [9] density **scales linearly** with the number of constituent quark participants [8]



[8] **ALICE** Collaboration, V. Zaccolo, IS2016

[9] **ALICE** Collaboration, PRL **116** (2016) 222302

[10] C. Loizides, PRC **94** (2016) 024914-Uses Empirical Recentered Formula

I rushed through "No Jets in p-p E_T" because:

This and many other relevant High Energy Physics issues in RHI physics are available in the new book by Jan Rak and Michael J. Tannenbaum, "High p_T physics in the Heavy Ion Era"

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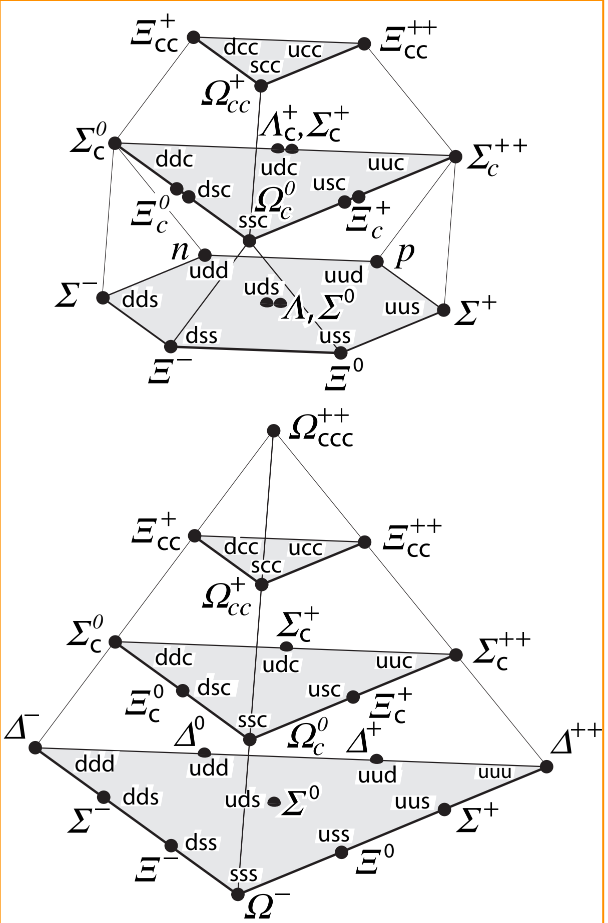
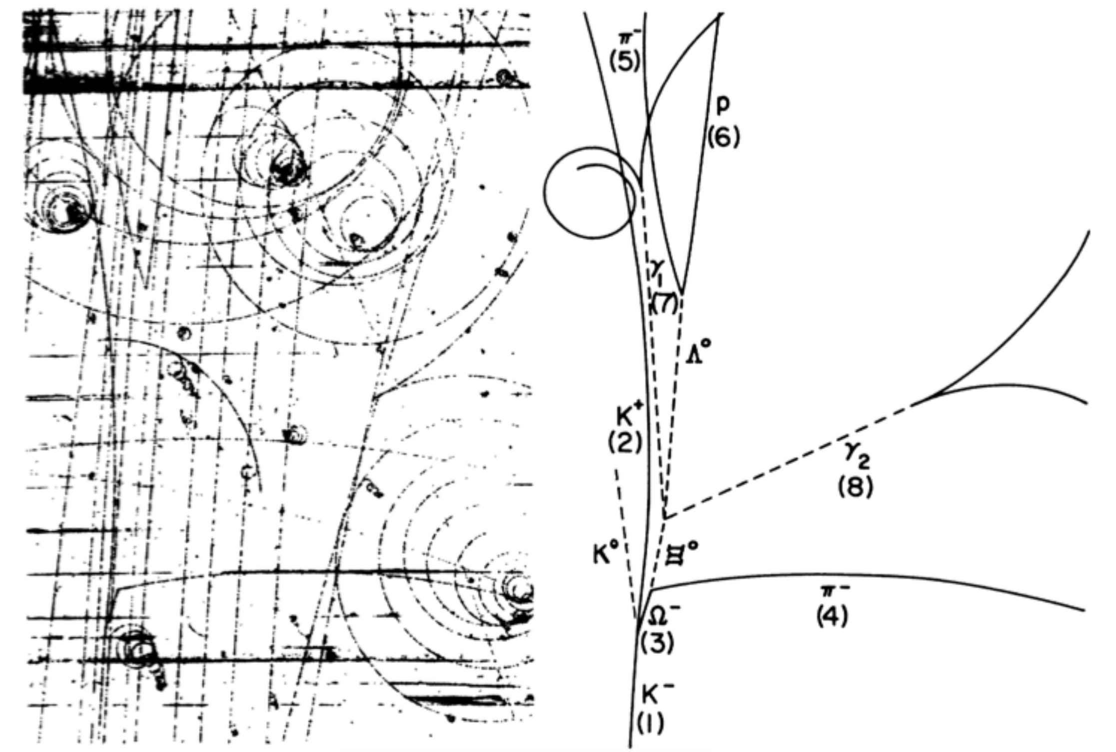
Constituent quarks are Gell-Mann's quarks from Phys. Lett. **8** (1964)214



Constituent quark model of Baryons



Ω^- (sss)

BNL-Barnes, Samios *et al*., PRL**12**, 204 (1964)

For more on Constituent quarks in QCD see E. V. Shuryak, Nucl. Phys. B 203, 116 (1982).